Demo R&D:

Taming the Plasma-Material Interface

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Outline

- **PMI-Based Mission Risks for a Component Test Facility (CTF) or Pilot Plant**
- **Requirements for a Plasma-Material-Interface Facility (PMIF)**
- **National High-Power Advanced Torus Experiment (NHTX) version of PMIF**

PMI Mission Risks - I

1. **Disruption heat loads to FW drive design to tritium breeding ratio < 1 ?**
   - A few unmitigated VDEs compromise FW in ITER.
   - Thick sacrificial surfaces are needed to survive disruptions.
2. **Disruption runaways to FW drive design to tritium breeding ratio < 1 ?**
   - Unmitigated runaways projected to be highly destructive.
   - Difficult to shield against MA's of multi-MeV electrons.
3. **ELMs result in divertor melting, cracking, thermal instability ?**
   - Very low allowable fractional energy loss must be maintained for high duty factor in CTF or Pilot Plant.
4. **High steady heat loads to FW inconsistent with thick surfaces needed for disruption survival ?**
   - Up to 5 MW/m^2 projected in some areas in ITER.
   - Requires thin plasma facing surface.

PMI Mission Risks - II

5. **Steady heat and particle loads result in unacceptable power loads, divertor erosion and/or redeposition ?**
   - Projections problematic, *e.g.*, $1/I_p$ scaling of λ_{SOL}, H-mode performance at high f_{Rad} and n/n_{GW}, measured erosion rates.

6. **Fuel and/or impurity influx from metallic (solid or liquid) FW and divertor degrade core plasma performance unacceptably ?**
   - ASDEX-U results with cold W and C-MOD results with cold Mo problematic with ICRF, advanced regimes.
   - No data with high T_{wall}, large area liquids, or high duty factor.

7. **Tritium inventory, throughput and/or permeation unacceptable ?**
   - No tokamak data with high T_{wall} or liquid metals.

8. **Dust and/or liquid accumulation from PFCs unacceptable ?**
   - Little tokamak data for extrapolation
   - No experience with real-time control.

Overview of PMI Challenges

PMI Parameters	KSTAR	JET ILW	ITER	FDF	ST-CTF	Pilot-AT	Pilot-ST	ARIES-AT
W/S (MJ/m^2)	0.052	0.118	0.626	0.608	0.632	0.721	0.901	1.631
Exp(2.5*Ip)	1.48E+02	2.20E+04	1.93E+16	1.47E+07	1.07E+13	8.00E+08	3.49E+19	1.30E+14
W/R (MJ/m)	1.63	6.12	64.45	32.87	43.25	44.98	112.19	143.05
Ptot/S (MW/m^2)	0.45	0.27	0.24	0.68	1.07	0.69	0.68	0.83
Ph/R (MW/m)	12.84	13.04	20.03	29.28	56.96	36.87	60.01	58.22
T wall (deg. C)	~ 30	~ 30	~ 200	~ 700	~ 700	~ 700	~ 700	~ 700
Duty Factor	Low	Low	Low	High	High	High	High	Very High

Pilot Plant challenge ~ FDF, ST-CTF challenges (at $2 MW/m^2$)

Individual disruptions & ELMs ~ ITER

But P/R, wall temperature and pulse length / duty factor far exceed JET, KSTAR, EAST, JT-60SA, ITER

It is difficult (for me) to see how MFE can proceed with an FDF, ST-CTF or Pilot Plant without disruption results from ITER, neutron-materials results from a Point Neutron Source*, and PMI results from a high P/S, high P/R, hot walls, long pulse / high duty factor, toroidal PMI facility.

* Without this, what are we testing in a Component Test Facility?

An Accelerated Strategy for MFE

Neutron-Materials Interaction

Point Neutron Source

Scientific and Technological Feasibility

ITER

+ DD S/C Tokamaks

Plasma-Materials Interface

PMI Facility

Pilot Plant

Component Testing
Net Electricity
Reliability & Availability

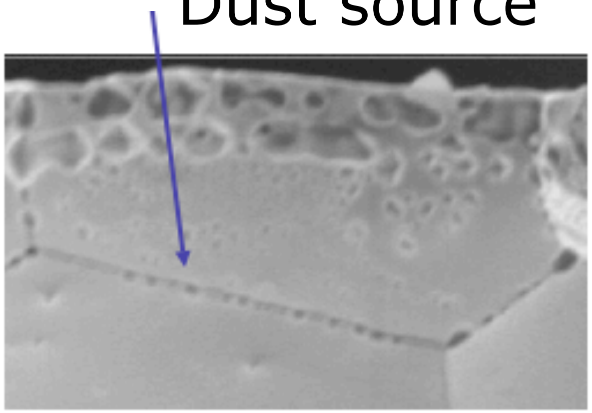
Strong research and technology programs are clearly needed, not just the major facilities.

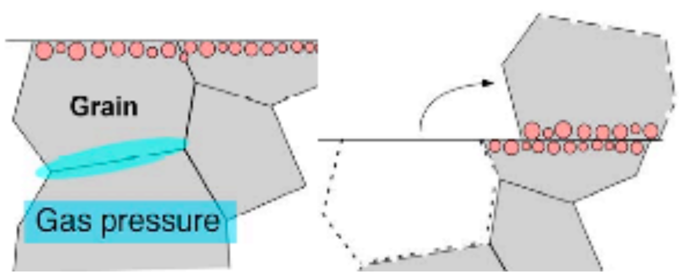
Requirements for a PMI Facility

- **High P/S ~ 0.8 - 1 MW/m^2**
  - To test first-wall solutions
- **High P/R ~ 40 - 60 MW/m**
  - To test divertor solutions
- **High T_{wall} ~ 700C**
  - To test fuel and impurity influx
  - To test tritium inventory, throughput, permeation
- **Long pulse, high duty factor**
  - To test PFC technology reliability (a PFC rather than PMI issue, per se)
  - To test ELM and disruption prediction, avoidance, mitigation
  - To test erosion / redeposition, evolution of surfaces, tritium retention & permeation
- **Neutron shielding**
  - Significant DD operation for pedestal, sputtering, core performance
  - Trace T operation for tritium retention and permeation studies
- **Excellent access**
  - Extensive diagnosis of all plasma-facing surfaces
  - Provision of helium and liquid metal services
- **Flexibility**
  - For alternative magnetic configuration and materials (solid and liquid)
  - For approaches to real-time dust and liquid removal

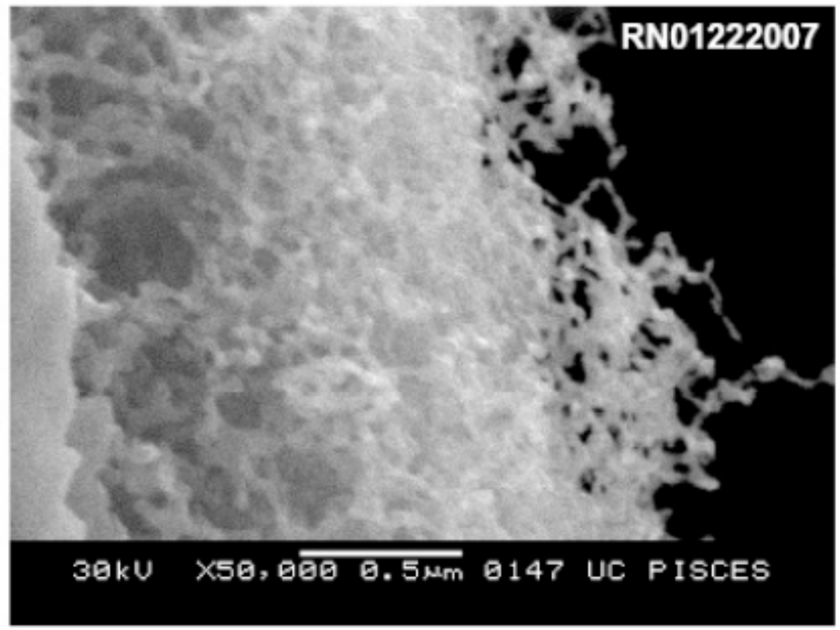
Tungsten Alloys must be Tested, but it is not Certain they will Work

Dust source





He-induced foam



Nagoya University

UCSD

At high fluence and wall temperature, dust and foam are serious concerns

Require capability to monitor and remove dust during operation

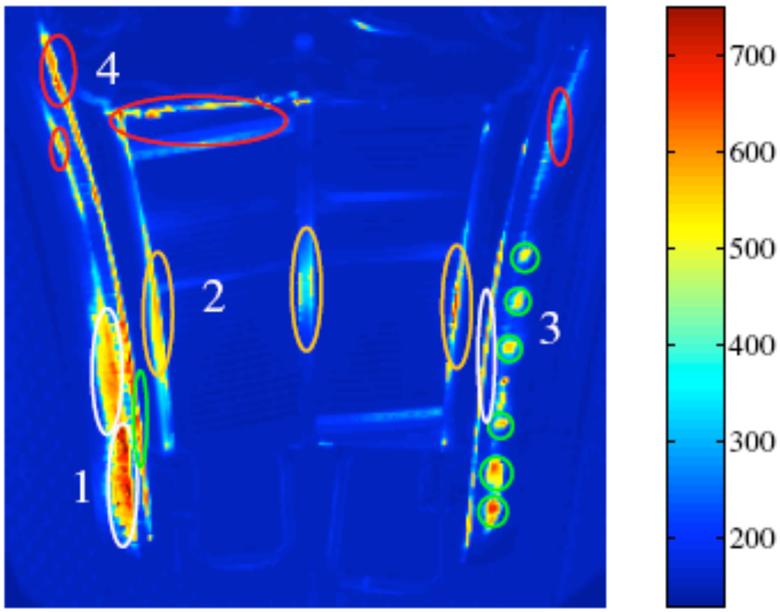
Testing must be at relevant conditions, including wall temperature

The Ability to Test Liquid Metal Divertor Solutions is Needed

FTU, Italy
Capillary Porous System (CPS)
T_{max} = 550 C
> 10 MW/m^2 in T-11
Self-shielding radiative layers observed.

- Successful tests of lithium in TFTR, T-11, FTU, CDX-U, NSTX
  - NSTX testing liquid lithium divertor
- Reduces recycling, improves confinement
- E-beam test to 25 MW/m^2 for 5 - 10 minutes, 50 MW/m^2 for 15s.
- Plasma focus test to 60 MJ/m^2 off-normal load
- Direct route to tritium removal, no dust, no damage?

Access for Diagnostic, Heating, Current Drive and PFC Services is Critical



Tore Supra, France
ICRF antenna

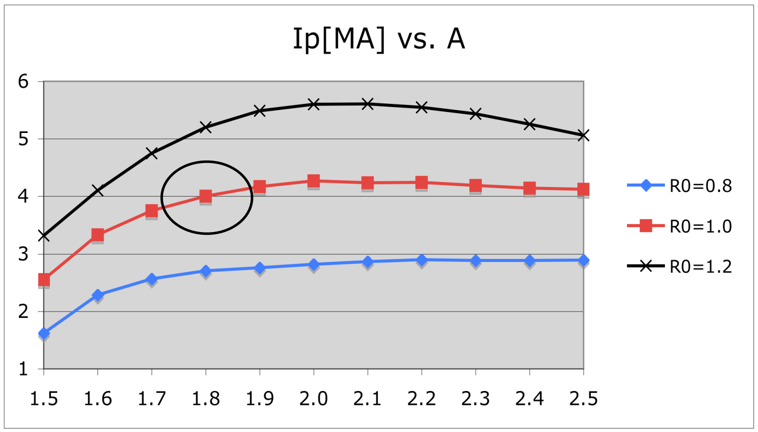
Figure 10. IR image of antenna Q1 on shot TS33748 at $t = 63.7$ s. Unit is °C. Superimposed on the image, a selection of zones on the front faces, classified according to their sensitivity to different sources of additional power are: zone 1 (white): mainly sensitive to the total power, zone 2 (orange): mixed total ICRF power and private ICRF power, zone 3 (green): sentitive to LH power only and zone 4 (red): predominantly private ICRF power.

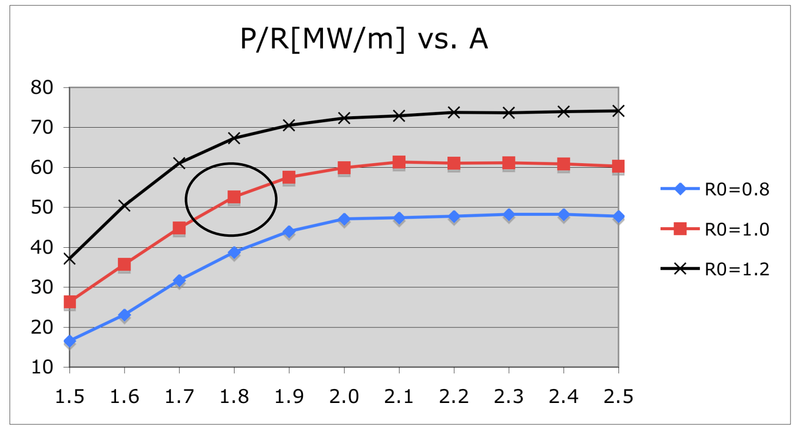
- **Extensive view in toroidal and poloidal angle of all plasma-material interactions**
- **Extensive in-situ surface analysis capabilities**
- **Extensive PFC engineering performance measurements**
- **A full set of advanced confinement, stability and sustainment diagnostics for high-performance operation**
- **A full set of advanced heating, current drive and control systems for high-performance operation without damaging ELMs or disruptions**
- **PFC services for heating, cooling and pumping will require substantial access**

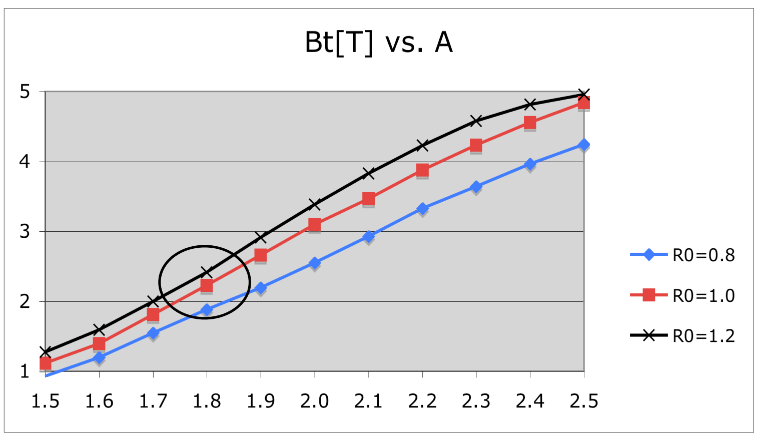
There are Some Outstanding Issues in Requirements Definition

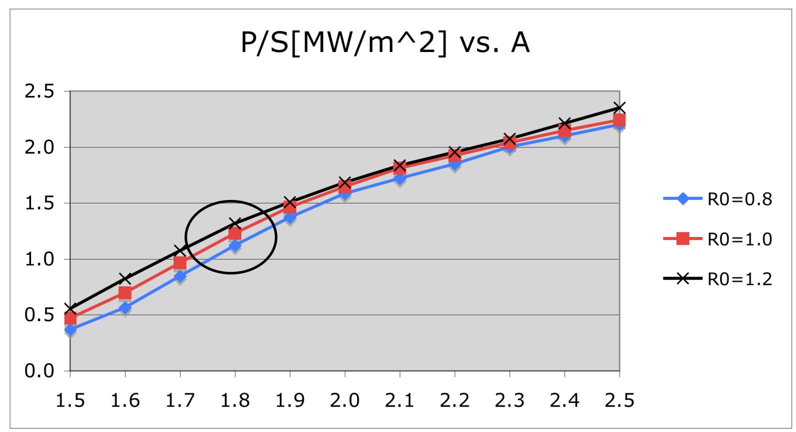
- **How long do individual pulses need to be and how high duty factor is needed?**
  - Tied to understanding of retention and permeation in hot metals.
  - Tied to understanding of erosion and redeposition of metals.
- **How close do we need to be in field strength and divertor angle to study erosion and redeposition?**
  - Tied to understanding of erosion and redeposition of metals.
- **How does power scrape-off width scale?**
  - Need to understand recent data from NSTX, DIII-D, C-MOD and JET.
  - Determine implications for power requirement, $q_{||}$, SOL collisionality.
- **Are there any significant cross-terms between neutron-material and plasma-material interaction?**
  - By far the dominant effects are on bulk properties that only affect PMI indirectly, but - for example - do we need to worry about neutron embrittlement of redeposited W flakes?

Design Point Scans Favor Low A







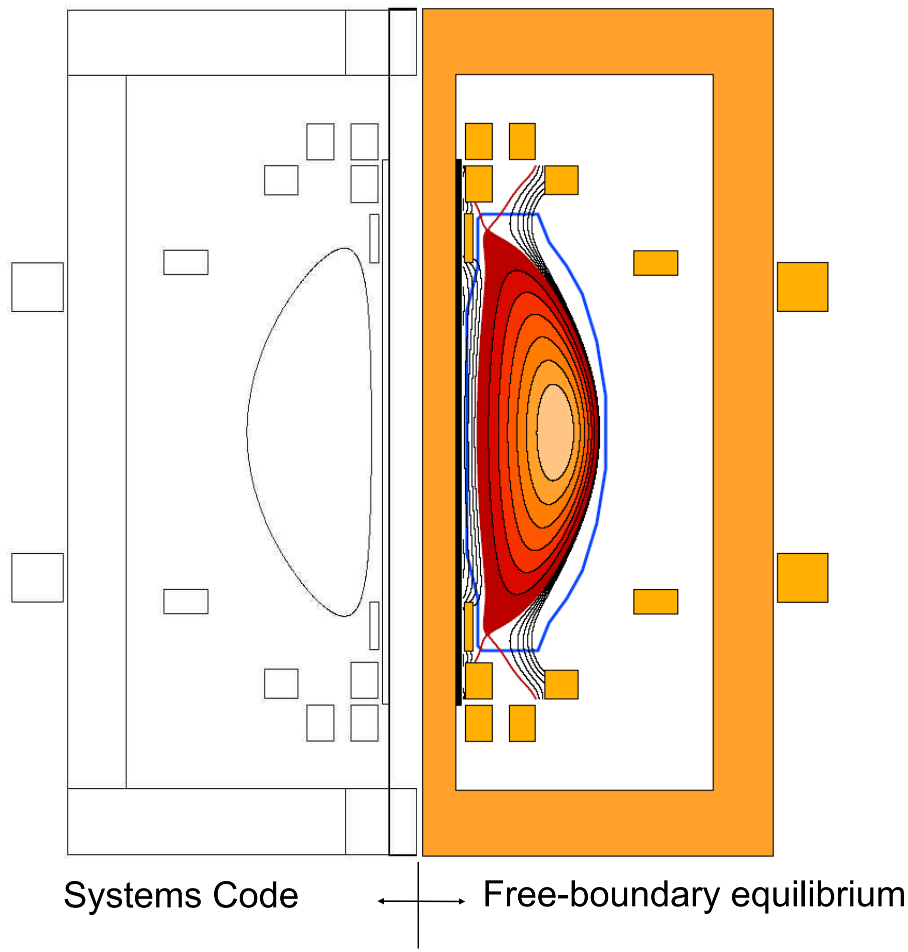


P/R and P/S goals at low size are met simultaneously at low aspect ratio

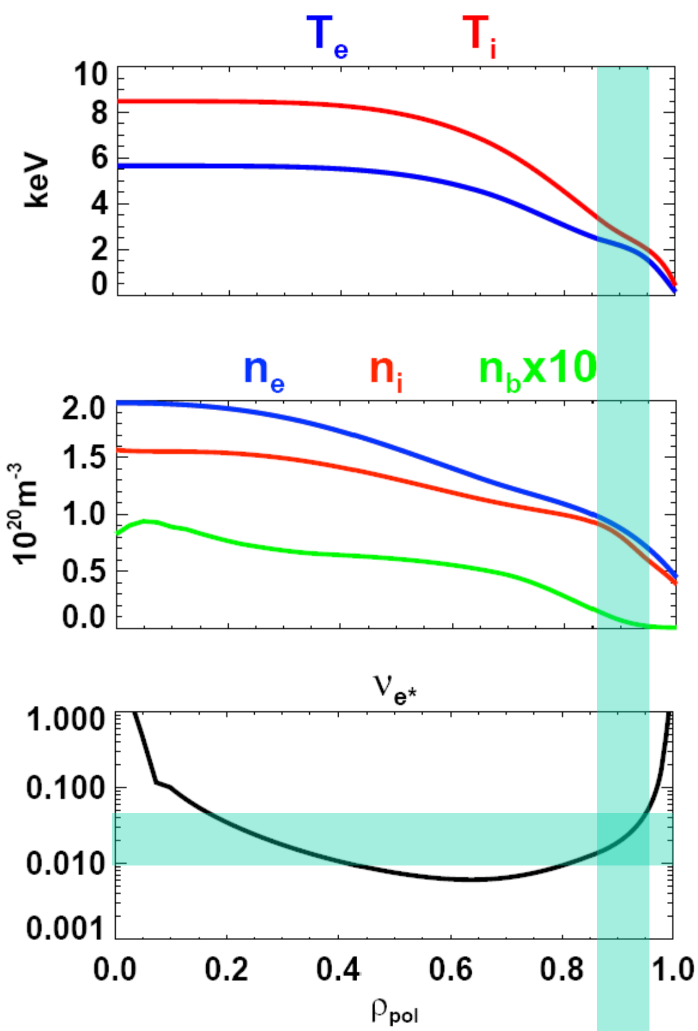
"Existence Proof" Design Point based on Minimum Electric Input Power

	DD
R0[m]	1.0
A	1.8
Ip[MA]	3.5
Bt[T]	2.0
kappa	2.7
Beta_N_total	4.5
fGW	32%
fBS	62%
HH98	1.30
P_aux[MW]	50.0
P/R [MW/m]	50
A_plasma[m^2]	43
P/S[MW/m^2]	1.15
delta	0.6
qcyl	3.47
Beta_T_total	15%
Beta_P	113%
ne[1/m^3]	1.10E+20
Tempavg[keV]	5.2
Flux_total[Wb]	1.9
R_inner_leg_TF [m]	0.281
drfw[m]	0.100
P_tf[MW]	86
P_oh[MW]	0
P_pf[MW]	38
P_aux_input [MW]	166
P_grid[MW]	300

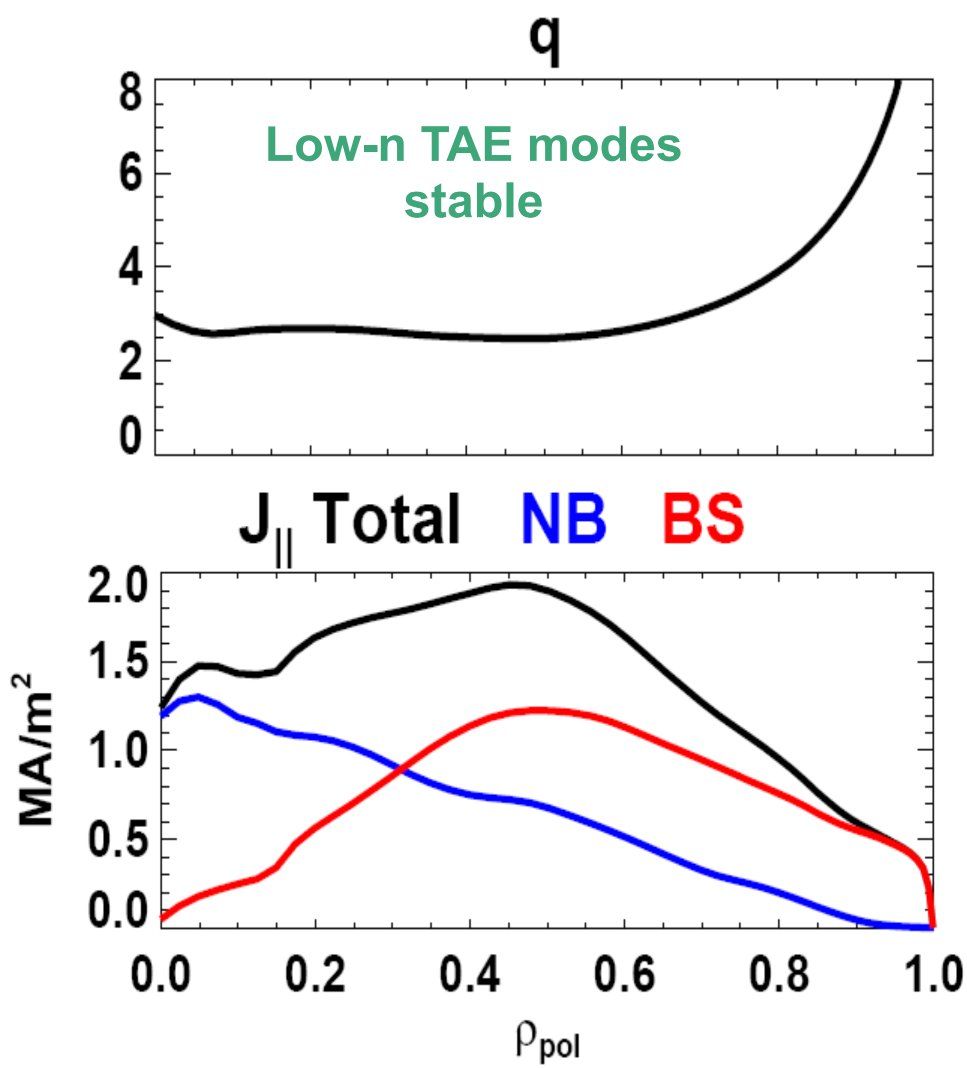
National High-power Advanced Torus Experiment (NHTX)



3 MA is Achievable with 30 MW of 110 keV NBI + Bootstrap; 20 MW RF Heating



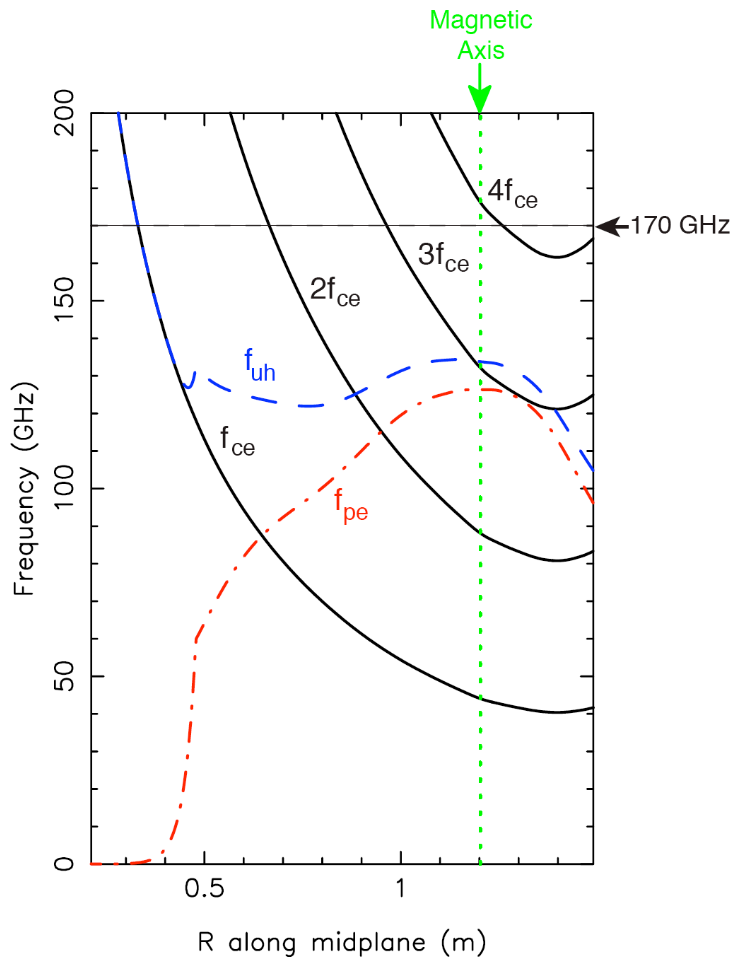
Pedestal ν_{e*} comparable to ITER

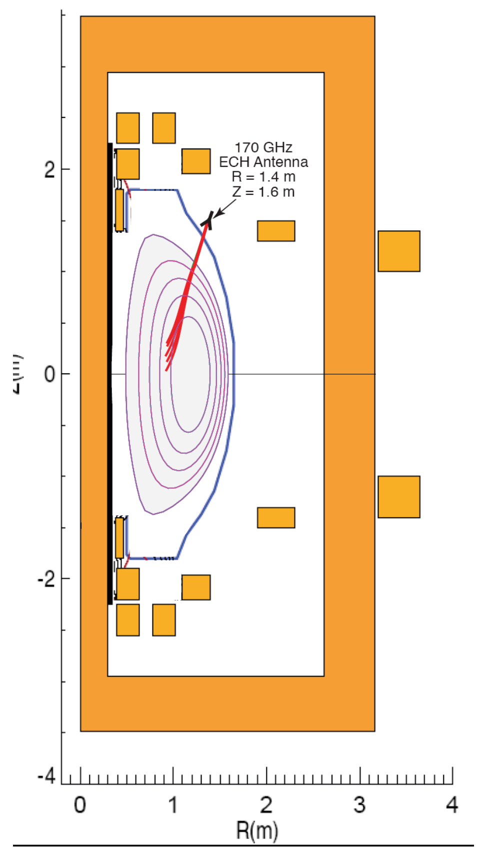


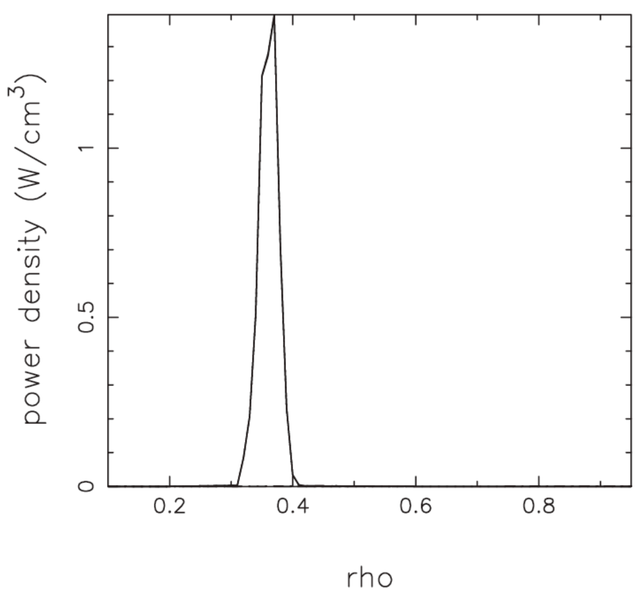
Transformer for start up and current ramp up, can test non-inductive techniques

170 GHz ECH Looks Practical

(successfully developed for ITER)



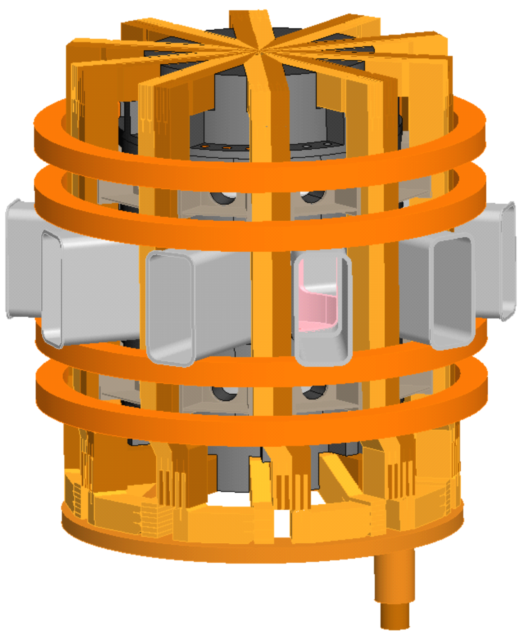


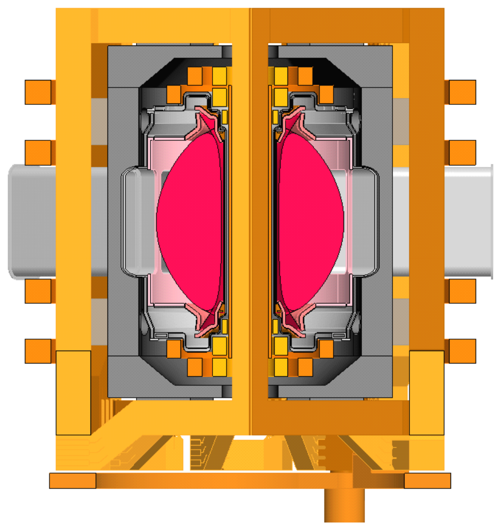


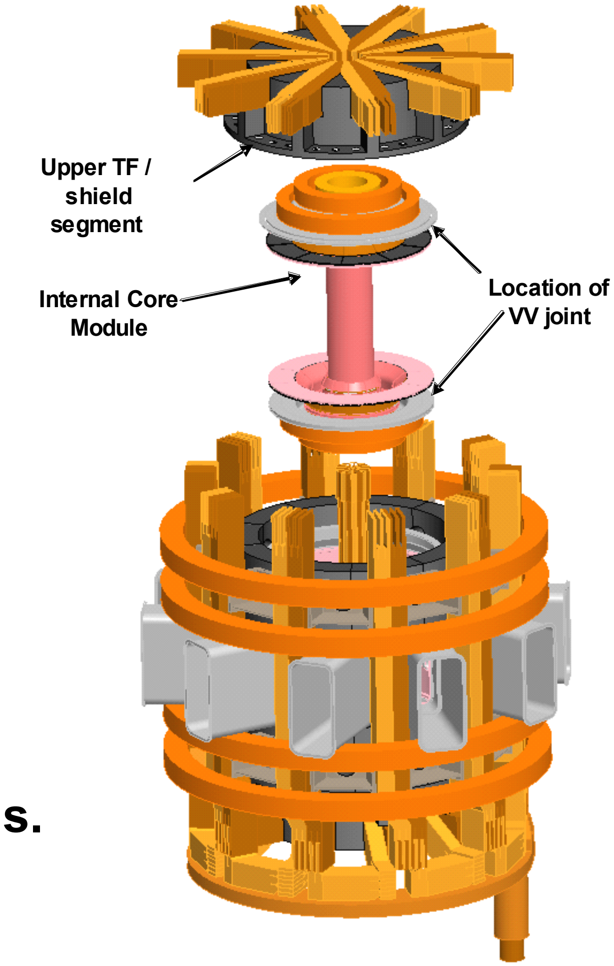
ICRH is also straightforward physics.

LHCD can be used to test current ramp-up.

R ~ 1m, A ~ 2, B ~ 2T with Steady State Cu Coils is Accessible and Flexible







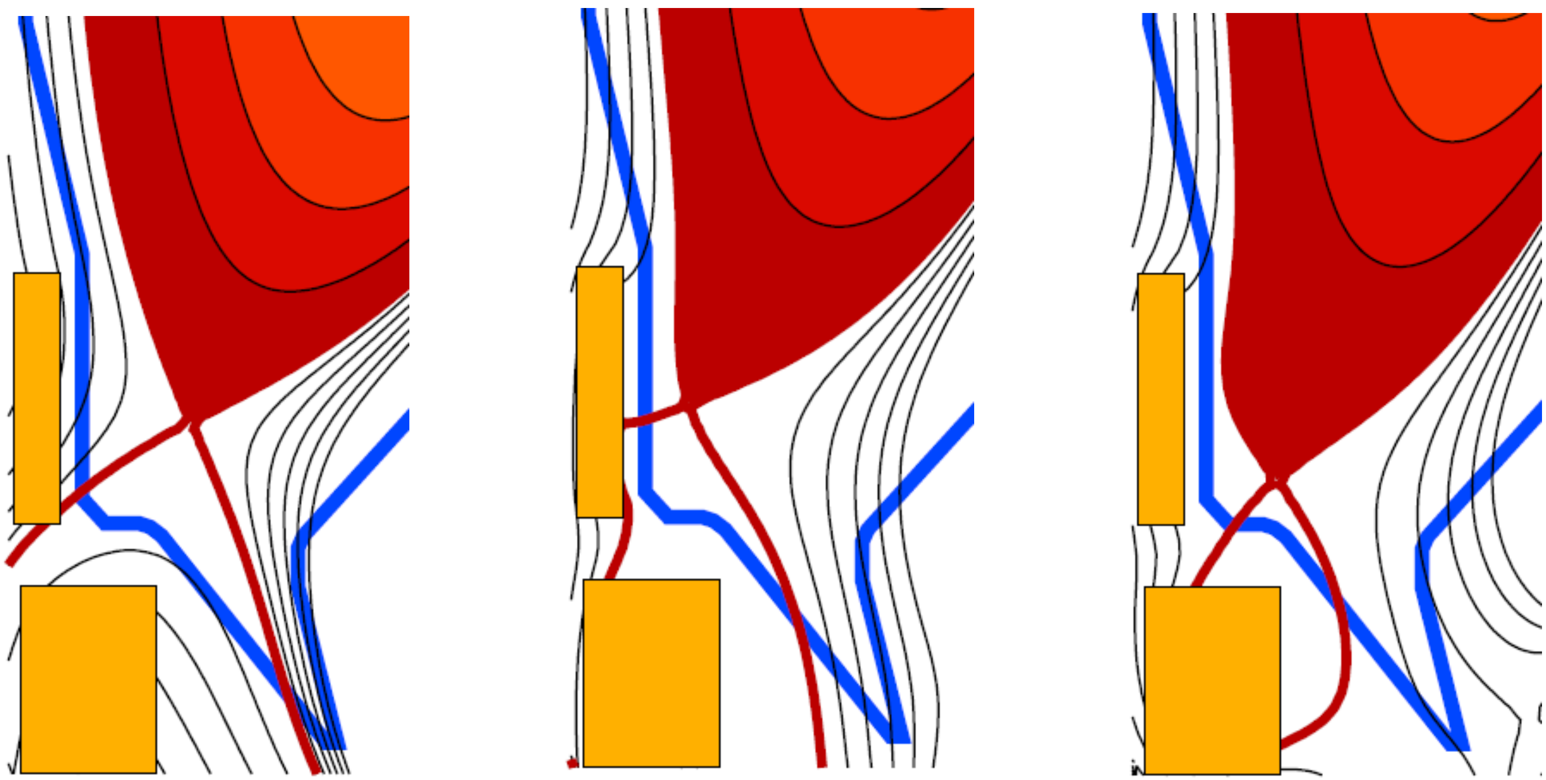
Good radial and tangential access at ~ all elevations.

Accommodates 30 MW of NBI H&CD.

50cm shield provides hands-on external access with 10^6 sec per year of DD operation.

Vertical access allows swap-out of divertor and divertor shaping coils.

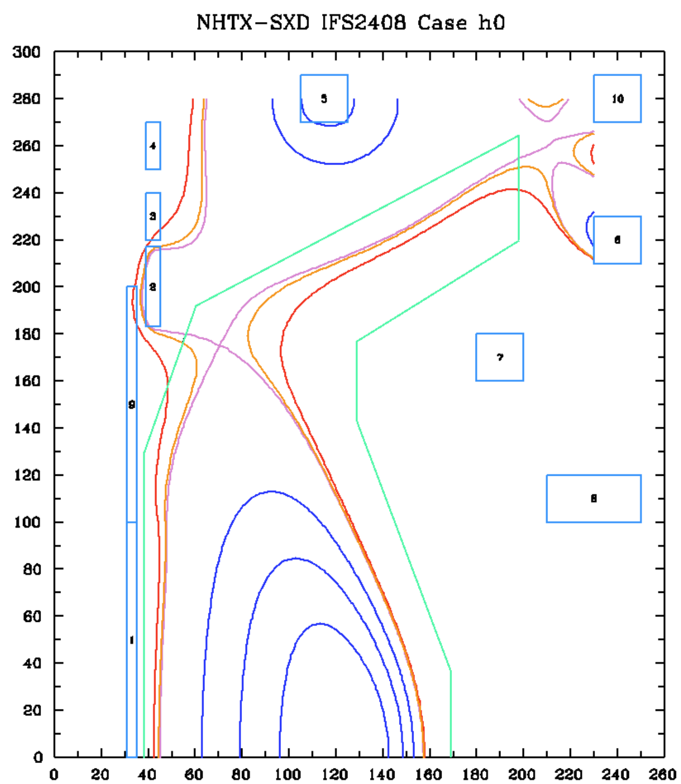
First PF Design Provides Wide Range of Flux Expansion

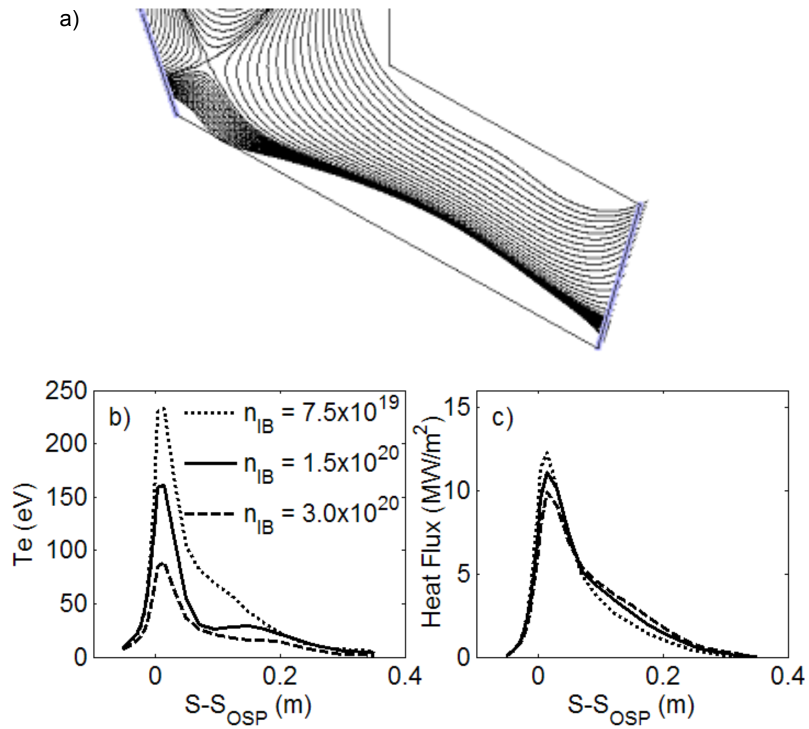


x 7.5 x 23 x 40

Heat flux expansion from midplane

NHTX Can Accommodate a Super-X Divertor





- **Field lines intersect divertor plate at greater than 1° angle**
- **With 5% Li evaporative cooling, peak heat flux drops to 2.5 MW/m^2, T_e ~ 5 eV, Z_{eff} = 1.6 at the plasma edge**

Conclusions

- **The PMI-based Mission Risks to a CTF or Pilot Plant are daunting.**
- **An accelerated strategy based on ITER + Point Neutron Source + PMI Facility looks attractive.**
  - Strong research and technology programs are clearly needed, not just the major facilities.
- **The requirements for a facility to mitigate the PMI risks (or determine that they cannot be mitigated) are fairly well defined.**
  - There are some outstanding issues to be resolved.
- **An R ~ 1m, a ~ 0.5m, B ~ 2T steady-state Cu-coil machine with high power NBI + RF seems well suited to the mission.**

Concept
for an
Integrated SOL-PMI-PFC
Test Facility

R Goldston, S Zweben, A Brooks, C Gentile,
M Jaworski, H Ji, R Kaita, H Kugel,
Y Raitses, J Rhoads, C Skinner, D Stotler,
JR Wilson, I Zatz

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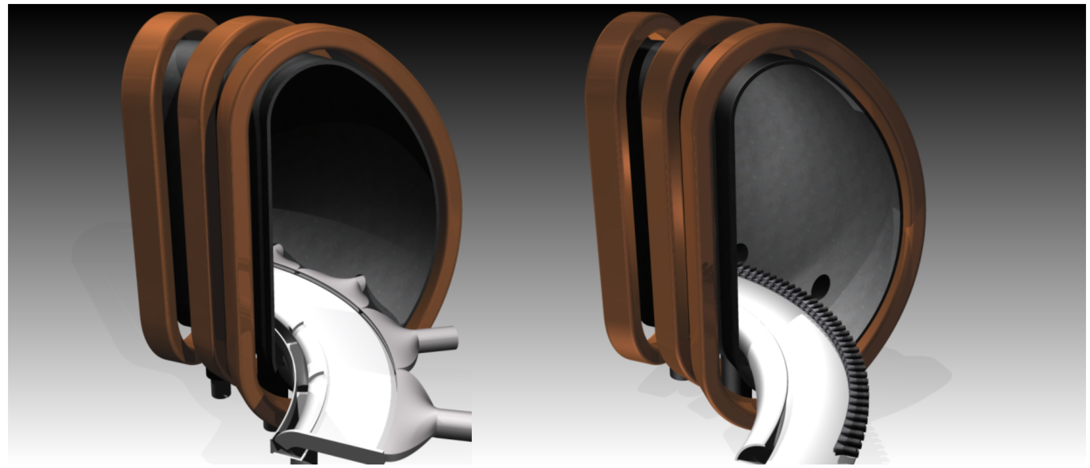
Laboratory - Directed R&D

Need Integrated Capabilities for Integrated SOL-PMI-PFC Tests

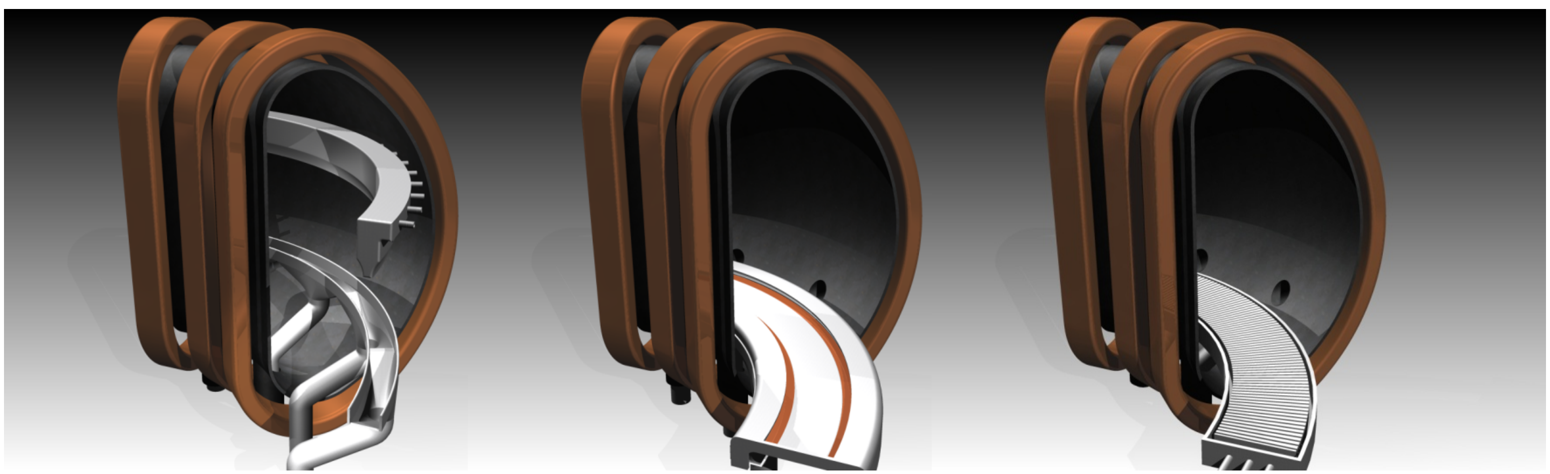
- **Realistic tokamak SOL-like plasma impingement** to test radiative self-shielding, distant redeposition, pumping
- **Realistic highly tangential magnetic field structure** to test erosion and local redeposition, liquid metal flow across ***B***
- **Extensive diagnostics**
  - SOL-like plasma, PMI physics, PFC technical operation
- **Would complement other facilities world-wide**
  - Combination of SOL-PMI-PFC physics / technology

Heat Removal with Fast-Flowing Li

- Designs use convection to exhaust incident power
- Velocity ≈ 10m/sec
- Thickness ≈ 1 cm



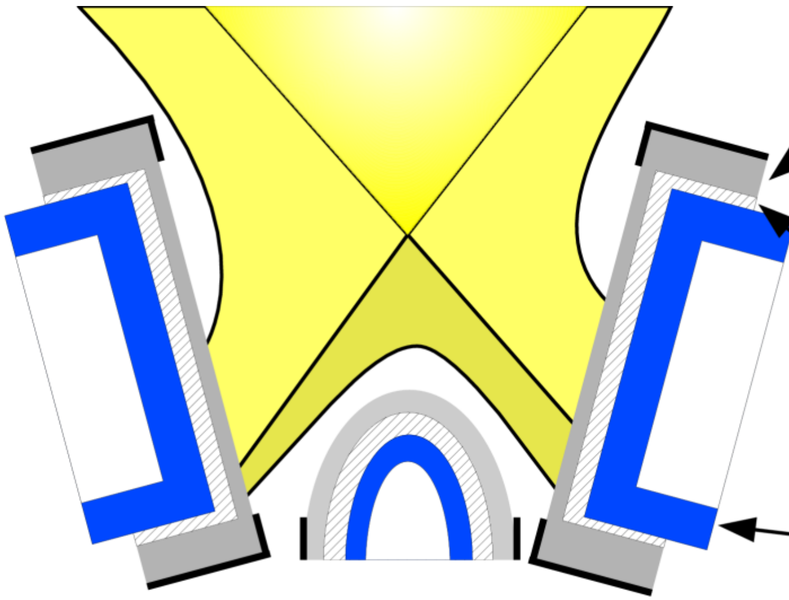
Pressure driven   Jets



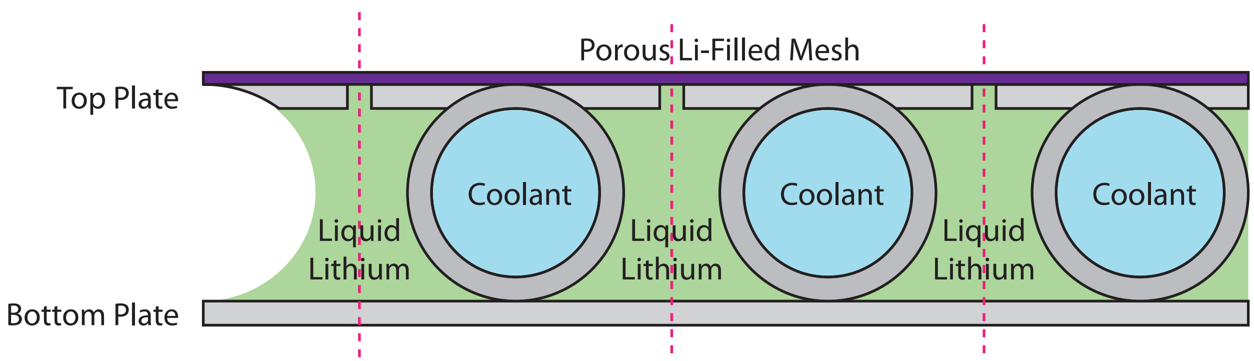
Curtain Limiter   JxB   TEMHD

H. Ji, J. Rhoads

Capillary Porous Lithium with Active Cooling



- Lithium "soaker-hose" wets plasma-facing surface
- Gas coolant
  + evaporation
  + radiation
  removes heat



M. Jaworski

Draft Magnetic Field and Geometry
for First Phase of SOL-PMI-PFC Test Facility

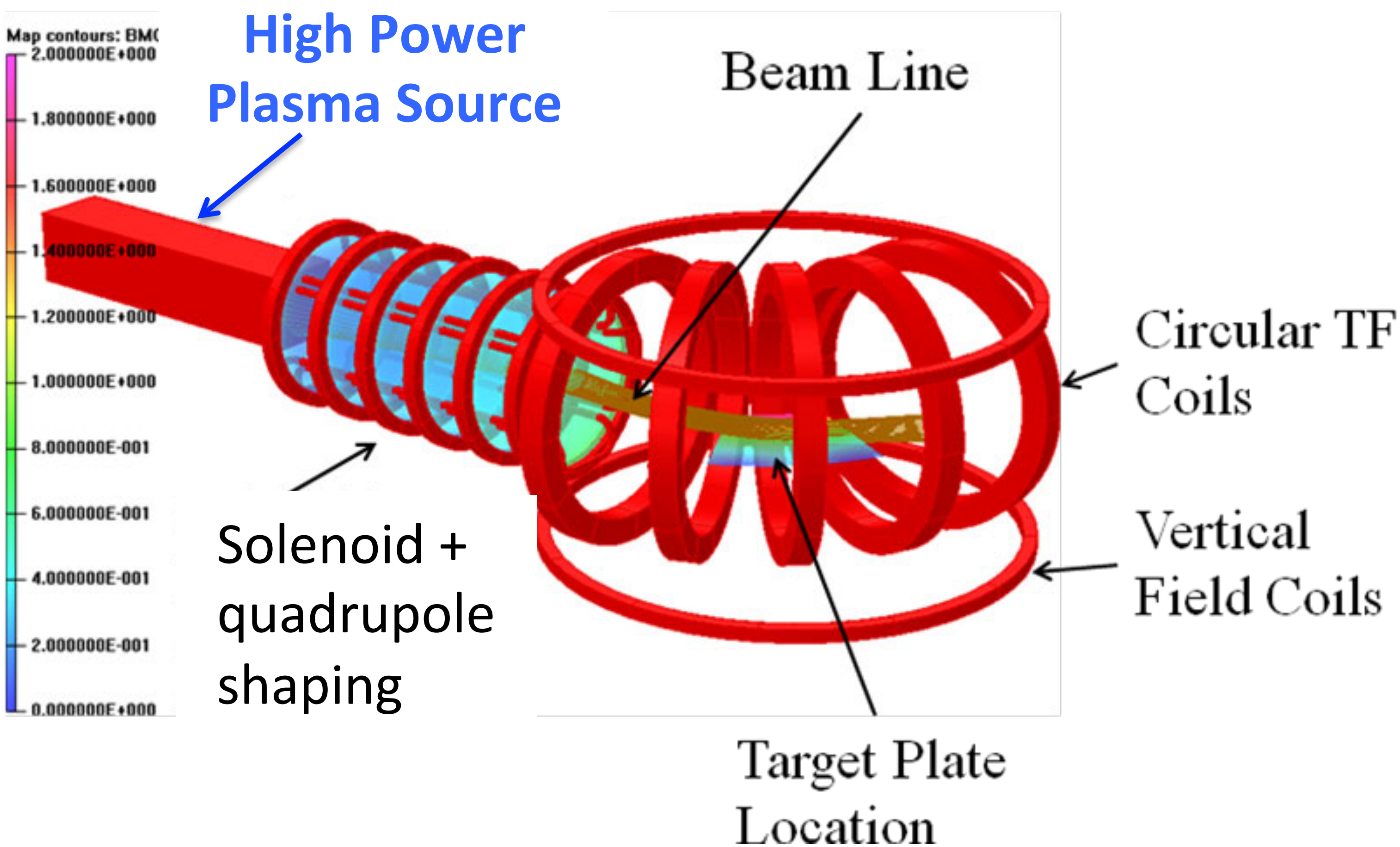
- **Toroidal magnetic geometry** is required to simulate flows of liquid metals in the radial direction of a tokamak.

- **1 T magnetic field** (modeled on NSTX-U for now)
  - dB/dR = 1.25T/m (implies R_o = 0.8m)
  - 0.025 – 0.125 T vertical B-field to model flux expansion

- **PFC component 0.5m in toroidal direction (1/10 of torus)**

- **Excellent access for plasma, PMI and PFC diagnostics**

A Quarter Torus Provides Specified Fields



Draft Power and Plasma Flux
for First Phase of SOL-PMI-PFC Facility

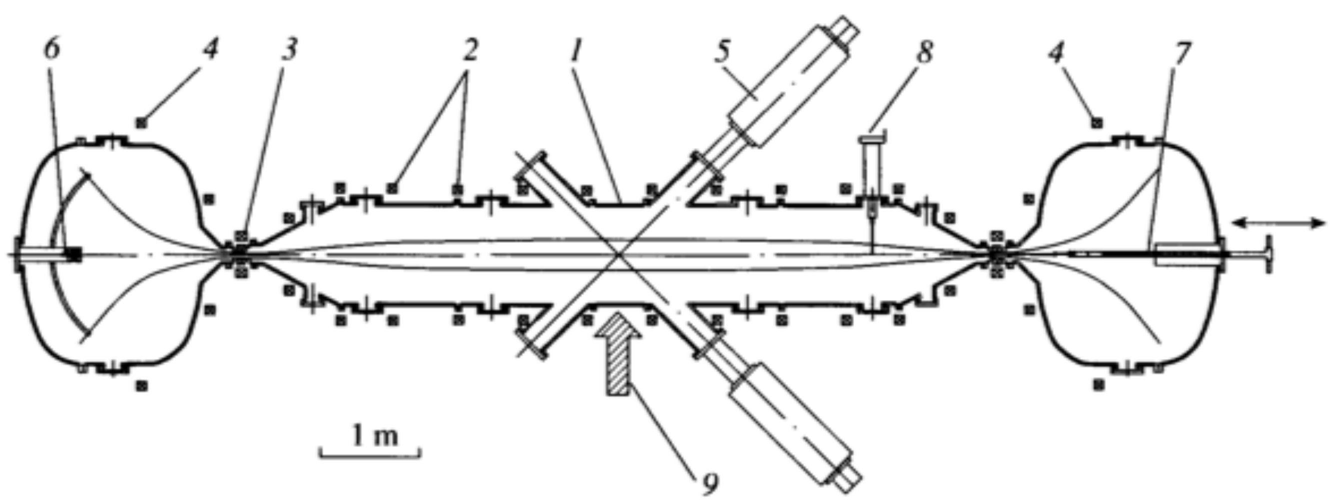
- **P/L in the toroidal direction up to 2MW/m**
  - **Implies up to 1 MW delivered to target**
  - **5 second pulse adequate for first phase (liquid surface)**
- **Heat flux width variable from 0.2m to 0.04m**
  - Implies local heat flux of 10 – 50 MW/m^2
- **Implies heat flux parallel to 1T B ≈ 400 MW/m^2**
  - **25 cm^2, 1 T ⇒ $\Phi = 2.5\ 10^{-3}\ m^2T$ = 2.5 mWb**
- **An upstream plasma ≈ tokamak edge covering 2.5 mWb at 1T would allow realistic tests of SOL, PMI and PFC effects.**
  - **Can an ICC provide such an upstream plasma?**

Gas Dynamic Trap Plasma
Approximates Tokamak Edge

- **Upstream parameters of T_e = 50 – 100 eV, n_e = 2 – 5 $10^{19}/m^3$** would provide the right Spitzer parallel heat flux and collisionality, so realistic $T_e(z)$ for radiative self-shielding.

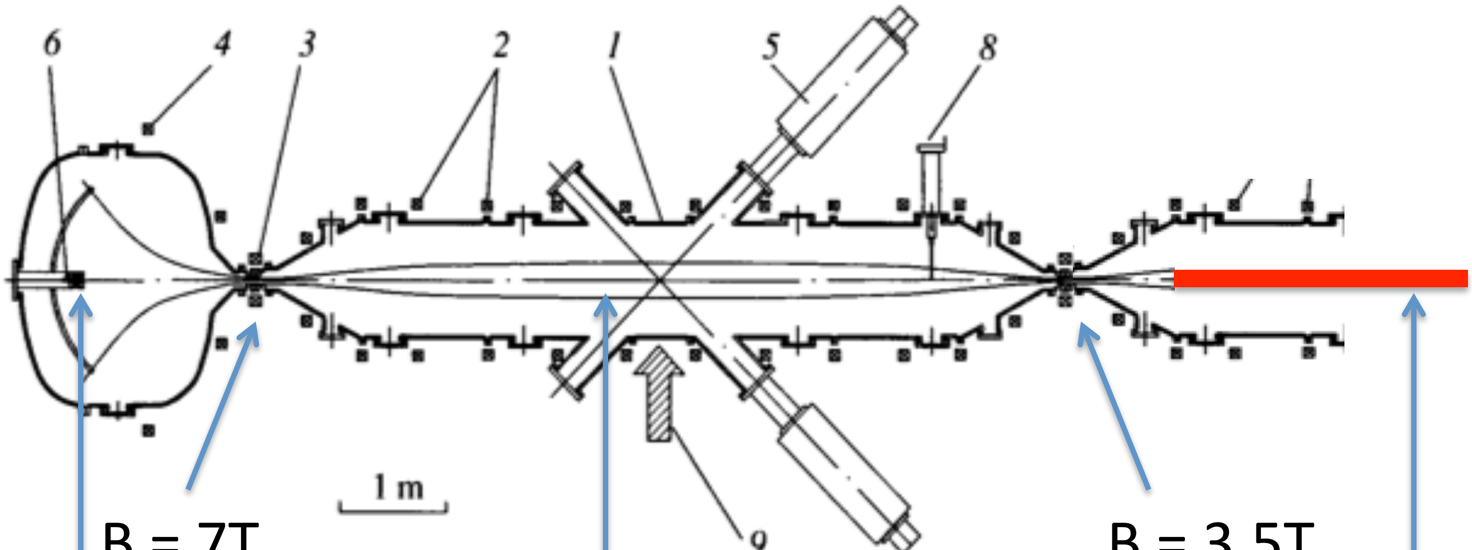
These are achieved today in the Gas Dynamic Trap, encompassing 4 mWb of flux !

- **But… pulse length at Novosibirsk is only 5 msec.**



Need to Change One End of GDT, Inject for 5 seconds, and Pump Aggressively

< 0.5 MW | 4 MW, 5 sec NBI | > 1 MW



To Target

B = 7T
M = 20

B = 3.5T
M = 10

Flux expansion > $(m_i/m_e)^{1/2}$

r = 0.06m, B = 0.35T
Φ = 4 mWb

r = 0.03m, B = 1T
Φ = 2.5 mWb

Needed Theory & Modeling

- **Equilibrium including non-axisymmetric quadrupole fields, toroidal curvature, non-axisymmetric distance to target**
  - Role of *ExB* drifts.

- **Energy and particle balance along and across *B***
  - Beam shine-thru and fueling *vs.* angle and energy
  - Optimization of heat flux to target

- **Interchange stability including various stabilization effects:**
  - GDT expansion
  - Cusp
  - Line-tying

Needed Experimental Confirmation

- **Place target in region of flux expansion ≈ 3.5.**
  - **Confirm $q_{||}/B$ ≈ 400 MW/Wb**
  - Measure heat flux to apertures along flux tube
- **Evaluate gas efflux and required pumping**
  - Examine operation with gas-puff from non-target end, to minimize pumping requirements.
- **Tilt target to examine effects of non-axisymmetry**
  - Add 1T solenoid region before tilted target?

GDT SOL-PMI-PFC Mission is Synergistic with GDT Neutron-Source Mission

- **Extending pulse length of GDT from 5 msec to 5 sec at today's plasma parameters = key step towards steady state**
  - Neutron production demo requires higher electron temperature, so operation with two flux expanders.
- **Budker Institute has already defined parameters for the next major step towards a neutron source:**
  - r = 0.06m $\rightarrow$ 0.06m
  - B = 0.35T $\rightarrow$ 1.4 T (Φ = 4mWb $\rightarrow$ 16mWb)
  - 15 MW, 100 keV D_0 NBI ($\approx$ 4 MW to PFC target)
  - Δt = 1000 sec
- **1.6 GW/m^2 for 1000 sec consistent with ITER SOL-PMI-PFC**
- **Full GDT neutron source consistent with Demo SOL-PMI-PFC**

Conclusions

- **An integrated SOL-PMI-PFC test facility would be a major tool for solving fusion's PMI problems.**
  - **It is not a simple undertaking to simulate even today's tokamak experiments.**
  - **A GDT could provide the upstream plasma.**
- **What is the cost/benefit trade-off *vs.* a high-power tokamak devoted to divertor development?**